

# AN ANALYTICAL MODEL FOR NON-UNIFORM MAGNETIC FIELD EFFECTS ON TWO-DIMENSIONAL LAMINAR JET DIFFUSION FLAMES

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## INTRODUCTION

In 1846, Michael Faraday found that permanent magnets could cause candle flames to deform into equatorial disks [1]. He believed that the change in flame shape was caused by the presence of charged particles within the flames interacting with the magnetic fields. Later researchers found that the interaction between the flame ions and the magnetic fields were much too small to cause the flame deflection. Through a force analysis, von Engel and Cozens [2] showed that the change in the flame shape could be attributed to the diamagnetic flame gases in the paramagnetic atmosphere. Paramagnetism occurs in materials composed of atoms with permanent magnetic dipole moments. In the presence of magnetic field gradients, the atoms align with the magnetic field and are drawn into the direction of increasing magnetic field. Diamagnetism occurs when atoms have no net magnetic dipole moment. In the presence of magnetic gradient fields, diamagnetic substances are repelled towards areas of decreasing magnetism. Oxygen is an example of a paramagnetic substance. Nitrogen, carbon monoxide and dioxide, and most hydrocarbon fuels are examples of diamagnetic substances.

Over the past twenty years, there has been an increase in the interest in the ability to control combustion behavior. Much research on the relation between combustion and magnetic fields has taken place in Japan. These researchers have found that the presence of magnetic fields caused significant changes in diffusion flame behavior, such as changes in radiative emissions from the flames [3], changes in flame shape and sizes [4-8], and changes in the extinction points [8]. However, this research has typically involved the use of electromagnets to supply the magnetic fields. One possible problem with this approach has been the interaction between the flames and the electric fields surrounding the coils used to generate the magnetic field [9]. As is known from research in magnetohydrodynamics, electric fields can interact with charged particles in fluids, causing physical changes in the fluid's behavior. The conclusions of the previous research have used order of magnitude analysis to argue that the electrical field interactions were insignificant when compared to the para- and diamagnetic behavior of the fluids involved in the combustion process [4]. Little research has been done on interactions between flames and the "pure" magnetic fields produced by permanent magnets to quantify this behavior without the presence of electric fields. This has primarily resulted from the lack of permanent magnets of strength comparable to that of electromagnets. Recent advances in material science have allowed for the commercial manufacture of rare earth permanent magnets with strengths on the order of 1 Tesla. In order to evaluate the usefulness of these magnets in altering flame behavior, a study has been undertaken to develop an analytical model to describe the change in the flame length of a laminar diffusion jet in the presence of a nonuniform magnetic field.

The analytical model derived for this study is an extension of the model derived by Roper for the investigation of slot diffusion flames in the presence of a gravity field [10]. In the cited reference, Roper derived expressions for the flame lengths from different types of burner geometries. His analysis showed that the length of flames from square and circular burners was independent of buoyancy effect. His analysis of slot burners revealed that buoyancy effects could not be neglected for this type of burner geometry. Using the Froude number, Roper identified three flow regimes for this geometry of burner; momentum controlled, buoyancy controlled, and transitional. Due to the nature of magnetic fields, the slot burner geometry lends itself well to an analysis of magnetic fields effects on diffusion flames.

By its nature, the para- and diamagnetic properties of matter make magnetocombustion behavior research an ideal choice for microgravity environments. Microgravity is useful for studying combustion behavior because the absence of buoyant forces simplifies the physical processes occurring during combustion. Within a microgravity environment, the interaction between the magnetic fields and the flames could be optimized, and greater understanding of the physical processes could be gained. However, the cost of designing and carrying out such an experiment requires that some type of initial analysis be performed to optimize the experiment design to obtain the greatest amount of meaningful data from the experiment. This analytical analysis represents the first step in this process.

## ANALYSIS

As stated previously, magnetic gradient fields exert a body force on para- and dia-magnetic materials. This induced body force is given by Kelvin's law:

$$\mathbf{F}_{MAG} = \frac{1}{2} \frac{\chi_i}{\mu_0} \nabla \mathbf{B}^2 \quad (1)$$

where  $\mu_0$  is the permeability of free space,  $\chi_i$  is the volumetric susceptibility of material  $i$ , and  $\mathbf{B}$  is the magnetic field. The volumetric susceptibility is  $O(10^{-9})$  for diamagnetic gases and of  $O(10^{-6})$  for paramagnetic materials. When a material is placed in another material of differing susceptibility within a magnetic gradient field, Kelvin's law causes a body force to be exerted, similar to that exerted by gravity on two materials of differing densities. This body force is given by

$$\mathbf{F}_{MAG} = \frac{1}{2} \frac{\chi - \chi_\infty}{\mu_0} \nabla \mathbf{B}^2 \quad (2)$$

where some gas of susceptibility  $\chi$  is in an atmosphere of susceptibility  $\chi_\infty$ . Assuming that the magnetic field is a function of  $z$  coordinate only, and that momentum and buoyancy forces are negligible, the conservation of momentum equation for the  $z$  direction may be integrated to give

$$v_z = v_{f0} \left[ -Pm \left( \left( \frac{B}{B_0} \right)^2 - 1 \right) \right]^{1/2} \quad (3)$$

where the magnetic pressure number is defined as

$$Pm = - \frac{(\chi - \chi_\infty) B_0^2 / \mu_0}{\rho_f v_{f0}^2} \quad (4)$$

where the subscript 0 on  $B$  defines the point at the burner exit, and all other notation is as used by Roper. [10] In order to obtain an expression for flame length as a function of magnetic gradient, it is necessary to assume the variation of magnetic field as a function of  $z$ . For the purposes of this study, a linear relation was defined as

$$B = B_0 - \Delta B z \quad (5)$$

where  $\Delta B$  represents the magnetic field gradient. Following Roper's method to obtain flame length expressions, the following expression is obtained:

$$\left[ \left( \frac{\Delta B}{B_0} L_{f,MAG} - 1 \right) \left( 2 \frac{\Delta B}{B_0} L_{f,MAG} - \left( \frac{\Delta B}{B_0} L_{f,MAG} \right)^2 \right)^{1/2} + \arccos \left( 1 - \frac{\Delta B}{B_0} L_{f,MAG} \right) \right] \quad (6)$$

$$= \frac{2}{Pm^{1/2}} \frac{\Delta B}{B_0} L_{f,MOM}$$

which implicitly defines the magnetic-controlled flame length,  $L_{f,MAG}$ .  $L_{f,MOM}$  is defined as the momentum controlled flame length as defined by Roper [10].

## RESULTS AND CONCLUSIONS

Figure 1 shows plots for three different values of  $B \cdot dB/dz$  for four burner ports of differing aspect ratios. The values for the port dimensions used in the calculations are shown on the plots in figure 1. The values for  $B$  and  $\Delta B$  are given in table 1. The fuel used for this study was propane in quiescent air. The flame temperature was taken as the adiabatic flame temperature of propane [11]. The volumetric susceptibility of air ( $\chi_\infty$ ) was calculated as  $3.74 \times 10^{-7}$ , and the value for propane was calculated as  $-3.21 \times 10^{-9}$ . The initial values for susceptibilities were obtained from [12], and were converted from molar value in cgs-emu system of units. It should be noted that the volumetric susceptibility for propane was corrected for the difference in density between the value given in [12] and the fuel density at the flame temperature.

From the plots in figure 1, it may be observed that changes in the product  $B \cdot dB/dz$  did not result in linear changes in the flame length as a function of flow rate  $Q$ . Instead, the flame length seemed to approach an asymptotic value for increasing  $B \cdot dB/dz$ . The rate of approach to this asymptote decreases with increasing  $B \cdot dB/dz$ . Roper showed that the flame length for a buoyancy induced slot flame would asymptotically collapse onto the burner with increasing gravitational field. It would be expected that the same phenomena would occur here with increasing  $B \cdot dB/dz$ . It may also be noted that the flame height is slightly influenced by the geometry of the burner port. These results show that non-uniform magnet fields can significantly alter the flame lengths of laminar diffusion flame. Further research is warranted to observe how different fuel and oxidizers affect this phenomenon, as well as how this affect compares to buoyancy effects and initial momentum effects.

## REFERENCES

- [1] M. Faraday, "On the Diamagnetic conditions of Flame and Gases," *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science*, vol. 31, pp. 401-421, 1847.

- [2] A. von Engle and J. R. Cozens, "Flame plasmas," *Advances in Electronics and Electron Physics*, vol. 20, pp. 99-146, 1964.
- [3] N. I. Wakayama, I. Ogasawara, and H. Hayashi, "The External Magnetic Field Effect on the Emission Intensity of the Na D Line in Hydrogen-Oxygen Flames," *Chemical Physics Letters*, vol. 105, pp. 209-213, 1984.
- [4] T. Aoki, "Radicals' Emissions and Butane Diffusion Flames Exposed to Upward Decreasing Magnetic Fields," *Japanese Journal of Applied Physics*, vol. 28, pp. 776-785, 1989.
- [5] T. Aoki, "Radical Emissions and Butane Diffusion Flames Exposed to Uniform Magnetic Fields Encircled by Magnetic Gradient Fields," *Japanese Journal of Applied Physics*, vol. 29, pp. 952-957, 1990.
- [6] T. Aoki, "Radical Emissions and Anomalous Reverse Flames Appearing in Upward-Increasing Magnetic Fields," *Japanese Journal of Physics*, vol. 29, pp. 181-190, 1990.
- [7] T. Aoki, "A Magnetically Induced Anomalous Ring Flame and Quenching Characteristics of Butane Flames," *Japanese Journal of Applied Physics*, vol. 29, pp. 864-867, 1990.
- [8] S. Ueno, "Quenching of Flames by Magnetic Fields.," *Journal of Applied Physics*, vol. 65, pp. 1243-5, 1989.
- [9] J. R. Carruthers and R. Wolfe, "Magnetothermal Convection in Insulating Paramagnetic Fluids," *Journal of Applied Physics*, vol. 39, pp. 5718-5722, 1968.
- [10] F. G. Roper, "The Prediction of Laminar Jet Diffusion Flame Sizes: Part I. Theoretical Model," *Combustion and Flame*, vol. 29, pp. 219-226, 1977.
- [11] S. k. Turns, *An Introduction to Combustion: Concepts and Applications*. New York: McGraw-Hill, 1996.
- [12] R. C. Weast, "CRC Handbook of Chemistry and Physics," , 67 ed. Cleveland: CRC Press, Inc., 1986.

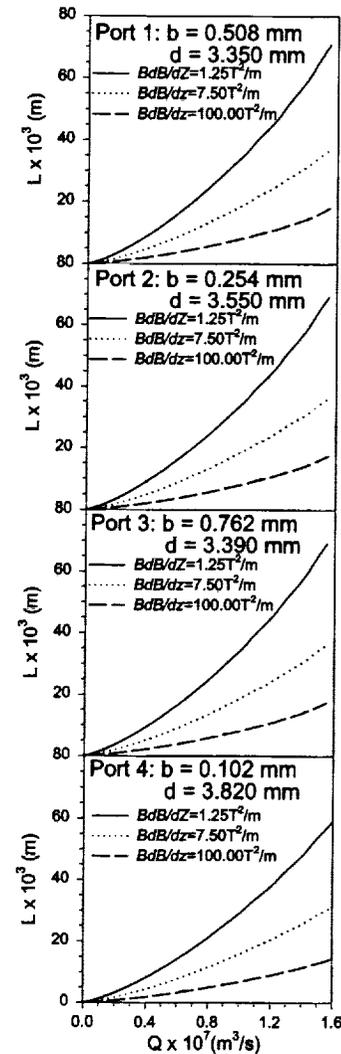


Figure 1: Predicted flame height as a function of flow rate and magnetic field.